QUANTITATIVE NONDESTRUCTIVE EVALUATION OF CARBON-CARBON COMPOSITES BY PULSED INFRARED THERMOGRAPHY

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INTRODUCTION

Among all the nondestructive evaluation (NDE) techniques that are used in industry, Stimulated Infrared Thermography (SIRT) is very attractive because of its noncontact and rapid-scanning ability [1]. In our laboratory, we applied this technique to composite materials which are often used in aerospace structures. In particular, we applied it to carbon/epoxy composites [2,3]. Due to the relatively low refresh frequency of the monocell IR cameras, the application of the method was restricted to low thermal conductors. Some new developments of the data reduction procedure were presented last year [4] to use this technique with good heat conductors. Satisfactory results were obtained in the case of delaminations in carbon/carbon (c/c) composites which will constitute the hottest parts of the thermal protection of the european space shuttle Hermes. A few months ago, we presented an improvement of this data reduction procedure which is able now to work with any kind of material and we applied it on the especially difficult case of the characterization of adhesive joints in metallic structures [5]. We present here the last results obtained in c/c composites by our SIRT techniques with the new data reduction procedure.

After a brief presentation of the experimental set up in the second section, the model and the identification procedure are explained in the third section. Results are given in the fourth section and compared with electron micrography examination, used as a destructive reference method, and with Compton back scattering, the other nondestructive method leading to satisfactory results. Finally, in the last section, a comparison is made between the present data reduction procedure and the one developed for low conductivity materials as carbon/epoxy composites. The compared accuracies and possible fields of application are determined.

THE THERMOGRAPHIC EXPERIMENTS

The sample used in this study is a 200 mm square plate of c/c composite material representative of the material which will be used for the hottest structures of the Hermes shuttle. This 3 mm thick sample contains natural defects in the core material. The defects to be detected and characterized are voids with a very small thickness compared to their extend.

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For our stimulated thermographic experiments, we use a strong source of radiative energy constituted of 9 IR lamps (18kW total electrical power). The temperature distribution of the sample surface following the heat pulse (typical duration 0.64s) is monitored by an IR camera Agema 880 LWB. The signal is numerized in real time and recorded on the hard disc of the micro-computer which supervises the experiment.

DATA REDUCTION PROCEDURE USED FOR C/C COMPOSITES

The Isothermal 1D Model

Let us consider a two layer sample of total thickness e, with a non perfect thermal contact at the interface (which is a defect in this case), located at a depth e_1 (see Fig. 1.a). We set : $e_2 = e-e_1$, and C_1, C_2 the volumic heat capacities of the first and second layers respectively. At every time after the pulsed heat deposition, the temperature distribution can be represented by the sketch of figure 1b. If we take into account the fact that the thermal resistance of the defect is much larger than the thermal resistances of both layers (which have high conductivities), each layer may be considered as isothermal, with temperatures $T_1(t)$ in the first layer and $T_2(t)$ in the second one. With these assumptions, and no losses, the energy conservation after the pulse leads to the following equations:

$$C_1e_1T_1+C_2e_2T_2 = Q \ , \tag{1}$$

$$C_1e_1\frac{dT_1}{dt} = -\frac{1}{R}(T_1-T_2) = -C_2e_2\frac{dT_2}{dt} \ , \tag{2}$$

in which Q is the absorbed fluence of the pulse.

In the case of a Dirac heat pulse, the initial temperatures (t=0) in the two layers are :

$$T_1(t=0) = Q / C_1 e_1, \quad T_2(t=0) = 0.$$

If we call :

$$T_\infty = \frac{Q}{C_1e_1+C_2e_2}, \qquad s = \frac{C_1e_1+C_2e_2}{RC_1e_1C_2e_2}, \qquad q = \frac{C_2e_2}{C_1e_1} \ ,$$

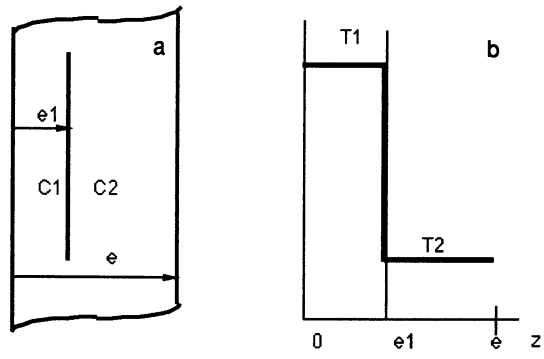

Fig. 1. Model used for defect identification in the case of high conductive materials.

1.a. Sample composed of two layers (subscript 1 and 2) with non perfect contact at the interface located at depth e_1.

1.b. Temperature profile in the sample of fig. 1.a after a pulsed heat deposition at z=0.

and using equations (1) and (2), one obtains:

$$\frac{dT_1}{dt} + s(T_1 - T_\infty) = 0 \ ,$$

the solution of which is :

$$T_{1D}(t) = T_\infty \ [1 + q \exp(- st)] \tag{3}$$

This solution can be extended to the case of a square pulse of finite duration τ (Duhamel theorem) and this temperature T_1 can be normalized (T_1^*) using the adiabatic temperature T_∞ reached at very large times :

$$T_1^* = \frac{T_1 - T_\infty}{T_\infty} = \frac{q}{s\,\tau}\left[\exp(s\tau) - 1\right]\exp(- st) \tag{4}$$

A data reduction procedure can be proposed for the identification of the depth e_1 and the thermal resistance R of the defect. According to eq. (4), the thermogram, in semilogarithmic scale, $\mathrm{Log}(T_1^*) = \mathrm{Log}(T_1^*(t=0)) - st$, is a straight line of slope:

$$- s = -(C_1e_1 + C_2e_2)/RC_1e_1C_2e_2 \tag{5}$$

and of ordinate at the origin :

$$T_1^*(0) = \frac{q}{s\,\tau}\left[\exp(s\tau) - 1\right] \tag{6}$$

The depth of the interface verifies the relation :

$$e_1 = \frac{e}{1 + \frac{C_1}{C_2}\,\frac{\tau\, T_1^*(0)\, s}{\exp(s\tau) - 1}}, \tag{7}$$

which allows an iterative determination of the depth e_1, once s and $T1^*(t=0)$ are experimentally determined in the graph $\mathrm{Log}T1^* = f(t)$. The procedure starts with the value $e_1 = e/2$ and stops when two successive values are close enough. In practice, five iterations are sufficient for a convergence better than 10^{-3}. Finally, the thermal resistance R characterizing the defect is given by the relation:

$$R = \frac{C_1e_1 + C_2e_2}{sC_1e_1C_2e_2} \ . \tag{8}$$

Procedure to Reach the Asymptotic Adiabatic Temperature T_∞

Let us recall that in order to use the very simple feature of the normalized thermogram in semilogarithmic scale, it is necessary to reach the experimental value of T_∞. Practically T_∞ cannot be determined easily from the thermogram because the characteristic time of convective losses is of the order of a few tens of seconds. Thus, the experiment should not

exceed such a time, and typically we used 10 seconds. But, if the thermal resistance of the defect is important the adiabatic temperature is not reached at that time.

Actually, it is always possible to determine T_∞ from the temperature $T_1(t)$ at any time t provided that, (i) heat losses have not affected $T_1(t)$ and, (ii) the signal to noise ratio is large enough. To improve the first point (i), we stop the analysis of the thermogram at a time t_{max}. It is difficult to find a universal criterion for the choice of t_{max}. Generally, we study the thermogram of a particular pixel and we choose t_{max} as the limit beyond which appears the temperature decrease which is characteristic of the beginning of the heat losses. To improve the second point (ii), let us recall that our experimental thermogram is given by :

$$T_1(t) = a + b \, .e^{(-s.t)} \tag{9}$$

from which we have to deduce a, b and c.

If we call T_{1max} the temperature at $t = t_{max}$, we can write :

$$\Delta T = T_1 - T_{1max} = b \, .(e^{(-s.t)} - e^{(-s.tmax)}) \tag{10}$$

which is a function of only b and s .

Now we calculate a weighted integral of ΔT :

$$I = \int_{t_{min}}^{t_{max}} \Delta T \; e^{(-p.t)} \, dt \tag{11}$$

in which t_{min} is roughly the time of the end of the heat pulse.

The purpose of this integral is to reduce the noise by increasing the weight of the temperature at the beginning of the thermogram and, on the contrary, to decrease the weight of the end of the thermogram which is much more noisy.

Finally to eliminate b from equation (11), it is necessary to evaluate I for two values of p (p_1 and p_2) and to calculate the ratio $I(p_1)/I(p_2)$ which depends only on s. The choice of p_1 and p_2 is not critical, but these two values must be chosen as different as possible, keeping in mind that if p_2 is too large the calculation of $I(p_2)$ will not be an exact integral but, actually, a finite sum of a few images : we generally take $p_1 = 1/t_{max}$ and $p_2 = 2p_1$. We have shown with numerical simulations that this procedure reproduces quite well the complete thermogram even if T_∞ is experimentally totally unknown.

QUANTITATIVE IMAGES OF DEFECTS IN COATED CARBON-CARBON SAMPLES

Depth and Thermal Resistance Images

The data reduction procedure previously described, is applied for each pixel of the successive thermal images obtained after irradiation of the sample by the heat source. Fig. 2 presents such a temperature image obtained on the Hermes material and Fig. 3 gives a normalized thermogram in semilogarithmic scale. This thermogram is obtained by collecting the values of the temperature of the same pixel in the successive thermal images. The pixel is located on a point above a defect and the thermogram is in agreement with the analytical expression : $Log(T_1^*) = Log(T_1^*(t=0) - st)$, allowing the experimental identification of the parameters s and $T_1^*(t=0)$ and consequently of the physical parameters defining the defect, e_1 and R. The same data reduction is applied for each pixel.From the successive thermal images it is then possible to calculate a depth image and a thermal resistance image which characterize completely the existing defects in the tested sample. Such synthetic images are given figures 4 and 5.

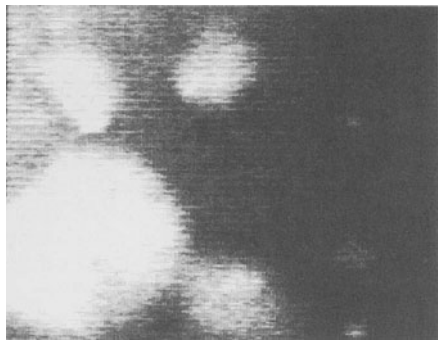

Fig.2. Thermal images of the front face of the sample 0.16 s after the end of the heat pulse.

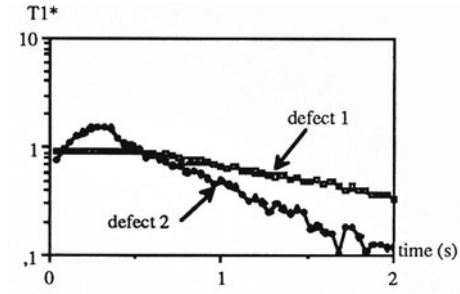

Fig.3. Normalized thermograms $T_1^*(t)$ in semilogarithmic scale obtained above two defects.

Comparison with Electron Micrography Examination

In order to check the quantitative characterization in depth and thickness of defects, it was necessary to get reference information from a micrography examination. The sample was cut in six different sites chosen on defects detected by thermography. The micrographies were performed using a scanning electron microscope with a magnification x30. Fig. 6 shows a schematic representation of these micrographies. They allow a direct evaluation of the depth and the thickness of the defects. Firstly, we observe a wide variation of the total thickness of the sample which is not taken into account by the characterization procedure. Secondly, we have to keep in mind that the cutting operation probably generates a modification of the defects.The depth profiles are in agrement with the hypothesis that delaminations and defects can be assimilated to thin layers of air in comparison with their spatial extend. The results are given in the following table for two defects.

Table 1 . compared accuracy between NDE by SIRT and destructive examination

		defect1	defect2
Depth (mm)	NDE	1.2	0.88
	micrography	1.4	0.80
	discrepancy	14%	10%
Equivalent air gap thickness(µm)	NDE	90	39
	micrography	100	20
	discrepancy	10%	95%

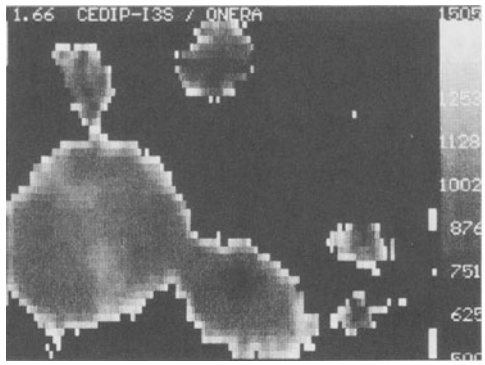

Fig.4. Location depth image in µm.

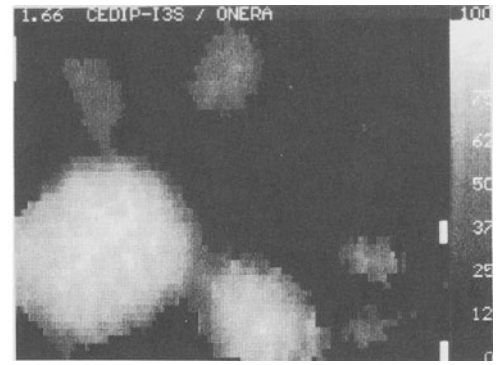

Fig.5. Equivalent air gap image in µm.

Comparison with Compton Back Scattering

A Compton back scattering experiment has been performed on the same sample of coated carbon/carbon by Aérospatiale. This method is currently used with composite materials as a characterization and non-destructive testing method. It is able to achieve, with a very good accuracy, local thickness and density measurements. The principle of the method is to count photons back scattered by a small volume inside the sample defined by the incident X beam and the detector direction of sight [6]. Detection of defects is based on the X attenuation differences between air and the material. This method seems to be very interesting because as the SIRT it is a one side method and it can be applied to any material. Associated to a scanning system, it is possible to realize two-dimensional and three-dimensional images. Such an image is shown on Fig. 7 . It is obtained at a particular depth of 1mm and gives a similar view of the sample got by SIRT where the detection of defects is quite easy.

However, the image presented here is not so detailed than the SIRT image, especially the little defects which are closer from the front face than the big one, are not well identified. For a complete identification of defects it is necessary to perform an image for each particular depth where the information is needed. Such an experiment is not competitive compared to the SIRT because time consumption is higher.

COMPARISON WITH THE EFFUSIVITY METHOD AND RESPECTIVE FIELDS OF APPLICATION

The Effusivity Method

Let us recall the principle of the effusivity method applied to rather low conductors materials like carbon/epoxy composites.This method assumes that a semi-infinite sample is irradiated, without losses, by a very short pulse. On the front face, the temperature is given by :

$$\Delta T(t)=\frac{Q}{b_0\sqrt{\pi t}} \tag{12}$$

where Q is the absorbed fluence and b_0 is the effusivity of the material. When a defect is present (thermal resistance R at depth z) the temperature doesn't follow the previous relation. One can define an apparent effusivity (depending on time) by:

$$b(t)=\frac{Q}{\Delta T\sqrt{\pi t}} \tag{13}$$

The minimum value of the ratio $b(t)/b_0$ vs time and the time at which it occurs are characteristics of the defect [3]. These values allow the depth z and the thermal resistance R to be calculated.

Compared Accuracies

In order to determine the accuracy of both methods we defined the following non-dimentional parameters :

- $z^* = z/e$ depth of the defect divided by the total thickness of the sample
- $Bi^{-1} = kR/z$ inverse of the Biot number where k is the conductivity of the material and R is the thermal resistance of the defect.

Thermograms of the front surface illuminated by a Dirac pulse were calculated for different values of these parameters. These theoretical thermograms were used as experimental simulations and using both previously described procedures (section 1 and 5) we have recovered the parameters z^* and Bi^{-1}.

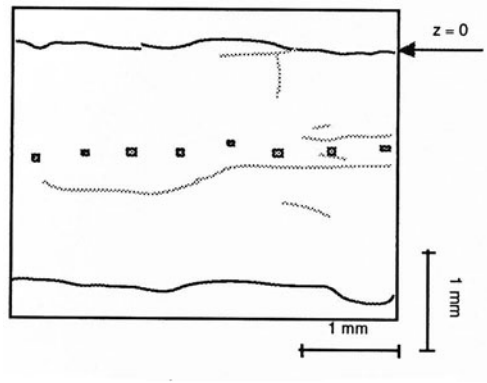

Fig.6. schematic representation of a micrography of a cross-section a-a.
▣ depth identified by thermography
crack seen on the micrography

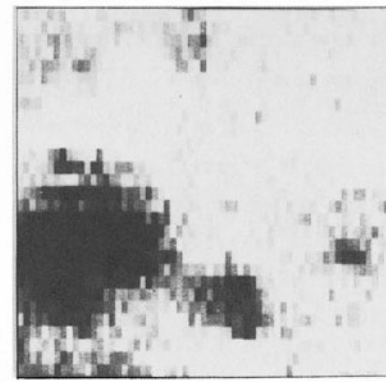

Fig.7. Image of the sample obtained by Compton back scattering at 1mm depth

As shown in figures 8.a and 8.b plotted for a particular value of z*=0.4, both methods have clearly complementary fields of application. The first method based on the isothermal model leads to good results for the highest value of Bi^{-1}.i.e. the highest values of the defect thermal resistance. Indeed for those cases the isothermal hypothesis is verified at best. In the same time, we see a better identification of z* than Bi^{-1}. This second result is due to the correlation between the two paramaters (Bi^{-1} depending on z). On the contrary with the second method based on the apparent effusivity the accuracy is better for the lowest values of Bi^{-1} but is much more dependent on the value of z*.The first method based on the isothermal model leads to good results for the highest value of Bi^{-1}i.e. the highest values of the defect thermal resistance. Indeed for those cases the isothermal hypothesis is verified at best. At the same time, we see a better identification of z* than Bi^{-1}. This second result is due to the correlation between the two paramaters (Bi^{-1} depending on z). On the contrary, with the second method based on the apparent effusivity, the accuracy is better for the lowest values of Bi^{-1} but is much more dependent on the value of z*.

CONCLUSION

The possibilities of the pulsed stimulated thermography as a non-destructive testing method for good conductor materials was demonstrated. The application on carbon-carbon composites shows that SIRT can be considered as a suitable industrial NDE method.

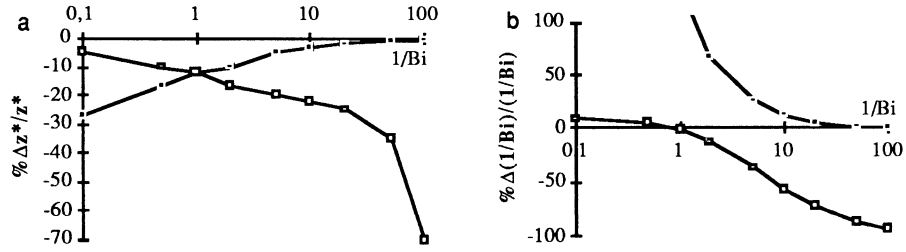

Fig. 8. Relative error in percent on the identification of z* (a) and Bi^{-1} (b) as a function of Bi^{-1} by the isothermal method (plain symbols) and the effusivity method (void symbols). The nominal value of z* is 0.4.

However, the quantitative evaluation involves choosing an adapted characterization method taking into account the thermophysical properties of the material and the expected characteristics of the defects. The 1D inversion procedure presented in this paper for good conductors leads to satisfactory results in a rather short time, provided that the hypothesis about defects are verified. Otherwise, it may be considered as the first quantitative step of an iterative procedure which takes into account heat losses and finite dimensions of defects.

NOMENCLATURE

	index i refers to layer i
e	total thickness of the sample
e_i	thickness
k	thermal conductivity
C_i	volumic heat capacity
T_i	temperature
T_∞	adiabatic temperature
$T_i^*=(T_i-T_\infty)/T_\infty$	adimensional temperature
t	time
τ	pulse duration
R	thermal resistance
Q	fluence
z	depth
$z^*=z/e$	adimensional depth
$Bi^{-1}=kR/z$	inverse of Biot number

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